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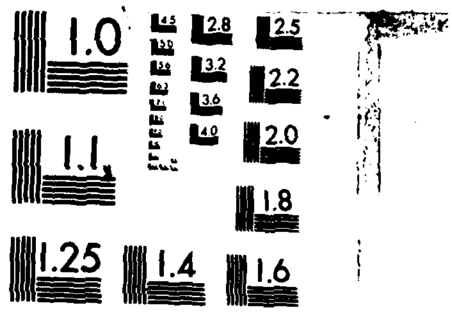

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The Global Positioning System (GPS) provides a new capability for establishing marine control for moored ocean bottom transponders that support precise navigation of ships, instrument packages, and submersibles. Autonomous remotely deployed marine platforms ranging to GPS satellites, which can simultaneously be triggered to measure acoustical ranges to a transponder network, can be used to establish geodetic control for the transponder array. The technique takes advantage of a dynamically changing double pyramid which is formed between GPS satellites and the transponder array linked observationally by the remote platform.

An error analysis is presented for an operational scenario where marine control is established in a deep ocean area. Several designs for this experiment are considered including the effect of constraint conditions. The results indicate that the establishment of precise ocean bottom control is obtainable using the GPS system with this approach.

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ERROR ANALYSIS FOR MARINE GEODETIC CONTROL USING THE GLOBAL POSITIONING SYSTEM

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ABSTRACT

The Global Positioning System (GPS) provides a new capability for establishing marine control for moored ocean bottom transponders that support precise navigation of ships, instrument packages, and submersibles. Autonomous remotely deployed marine platforms ranging to GPS satellites, which can simultaneously be triggered to measure acoustical ranges to a transponder network, can be used to establish geodetic control for the transponder array. The technique takes advantage of a dynamically changing double pyramid which is formed between GPS satellites and the transponder array linked observationally by the marine platform.

An error analysis is presented for an operational scenario where marine control is established in a deep ocean area. Several designs for this experiment are considered including the effect of constraint conditions. The results indicate that the establishment of precise ocean bottom control is obtainable using the GPS system with this approach.

This paper discusses the concepts involved, develops the mathematical models for these approaches, and presents an error analysis for each scenario.

1. INTRODUCTION

One of the most fundamental challenges presented by an ocean environment is the establishment of geodetic control systems similar to the geodetic networks on land areas. Therefore, methods to obtain accurate marine control which meet the requirements for solving various interdisciplinary problems will require innovative approaches. The applications of such ocean-bottom networks are numerous and well identified within the marine community by Saxena (1980).

In this direction, the Global Positioning System (GPS) provides such a capability. With respect to other current techniques for navigation with geodetic application in ocean areas, GPS would be the most versatile in its utility and global availability when fully operational. The immediate visibility of four to seven satellites anywhere on the earth's surface will make possible instantaneous positioning of a marine platform geometrically. Knowledge of such real time positions will eliminate complex mathematical modeling of platform motion on the ocean surface required of alternate approaches in the solution of the marine control problem.

At any instant, when the platform position is being obtained from GPS, instrumentation aboard the platform can simultaneously be triggered to measure acoustic ranges to a network of ocean bottom transponders. The concept takes advantage of a double pyramid (Figure 1), which is formed between GPS satellites and the transponders, linked via the marine platform. The use of remotely operating platforms may be extremely advantageous, providing flexibility and eliminating expensive budgets associated with conventional ship survey.

The measured ranges for any instantaneous double pyramid will constitute a geodetic "event" and these events are solved using the geometric positioning approach described by Mueller et al. (1973) and Kumar (1976), providing a geodetic control network in the marine environment. The present paper discusses the concept, developes the mathematical model for the system, and analyzes simulated results of this novel approach.

2. GEOMETRIC POSITIONING

Figure 1 constitutes a double pyramid, one inverted above the ocean between the GPS constellation and the marine platform and the other, normal, underneath it between the platform and acoustic transponders. The following sections include some pertinent details about GPS ranging and the acoustic links involved in the system.

2.1 The Inverted Pyramid

Range measurements to GPS are performed electronically by code correlation on each of two coherent L-band frequencies necessary for first-order ionospheric refraction correction. The geometric range between the receiver and the satellite transmitter, with the effect of clock synchronization error included, is known as a pseudorange. Error sources affecting GPS ranging are described and analyzed in Fell (1980).

It is assumed here that the geodetic receivers used in this application are capable of ranging to multiple GPS satellites simultaneously. The main observational function of an inverted pyramid is to provide instantaneous ocean surface position in the GPS coordinate frame. The uncertainty of a GPS range observation is currently estimated in the interval of 0.5 to 1.0 meters by Ward (1982) and positional recovery in a high accuracy navigational mode is anticipated to be 10 meters in each coordinate axis.

2.2 The Normal Pyramid

Position determination of marine control points including performance analysis of acoustic navigation systems and net-unit configurations is under extensive study by marine technologists (Knowles and Roy, 1972; Saxena, 1975; Durham et al., 1975; Yamazaki, 1975; Smith et al., 1975; Spindel et al., 1975; and Saxena, 1976 and 1981). The typical high resolution acoustic navigation technique considered here is a pulse positioning system. This system employs a transducer emitting acoustical pulses at a controlled repetition rate and acquires "replied" data from a set of bottom-moored acoustical transponders (Spindel et al., 1975). The slant range between the platform and transponder is estimated from the measured acoustic round trip travel time.

The uncertainty in the measurement of acoustical range R with an optimum pulse system is approximately:

$$\sigma_R = \frac{2Tc}{S} \qquad (1)$$

where c is the water sound velocity, T the duration time for a rectangular pulse, and S the peak signal to noise ratio (Spindel et al., 1975). Estimates of this uncertainty are about 1.5 meters for ranges less than 5 kilometers and 5 meters for greater ranges. The maximum observation distance was chosen as 8 kilometers in the analysis of this concept.

3. MATHEMATICAL MODEL

Detailed discussions on the geometric solution of the geodetic positioning problem using range observations are available in Krakiwsky and Pope (1967), and Mueller et al. (1973, 1975). Figure 1 illustrates the geometry for ranges r_{ij} between any transmitter P_i (u_i, v_i, w_i; $i = 1, 2, 3, \ldots$) and surface receiver Q_j (u_j, v_j, w_j; $j = 1, 2, 3, \ldots$), for example between the GPS satellite and the marine platform in the inverted pyramid configuration. At the same instant, the range R_{jm} between the platform and a moored transponder in the normal pyramid is implied. Then the following relations in the earth-fixed coordinate system of the GPS system can be written:

$$F_{ij} = (u_j - u_i)^2 + (v_j - v_i)^2 + (w_j - w_i)^2 {}^{\frac{1}{2}} - r_{ij} = 0 \qquad (2)$$

and

$$F_{jm} = (u_j - u_m)^2 + (v_j - v_m)^2 + (w_j - w_m)^2 {}^{\frac{1}{2}} - R_{jm} = 0. \qquad (3)$$

For actual observations, equations (2) and (3) would require certain modifications to represent systematic and random error sources (Fell, 1980; Hui, 1982; Wells et al., 1982; and, Harman, 1982).

These basic mathematical models are solved through trigonometric computations based on simultaneous observational events (Reilly et al., 1972). The geometric strength of the solution to the marine control problem will increase with more than four satellites or transponder stations (Blaha, 1971a; Escobal et al., 1973; Smith et al., 1975; Saxena, 1976). The optimal survey pattern for the remote platform will change with the water depth relative to transponder station chords (Smith et al., 1975). As the system extends with an increase of "i", "j", and/or "m" (Figure 2), the model equations (2) and (3) become overdetermined and the unknown transponder positions are then recovered through least squares adjustment. Parametric constraints are introduced as appropriate.

3.1 Observation Equations

Equations (2) and (3) are linearized by Taylor series using preliminary values for the satellite survey platform, transponder positions, and observed ranges r_{ij} and R_{jm} to obtain observation equations (Uotila, 1976) in the following form:

$$BV + AX + W = 0 \qquad (4)$$

In this paper, as a first step, a less complex adjustment procedure is adopted. Equation (2) is not linearized directly into equation (4), but the inverted pyramid is solved initially to obtain the approximate platform positions (u_j^o, v_j^o, w_j^o) for use in any normal event at time t_k. This is equivalent to adopting the GPS navigation solutions as initial platform coordinates in the simplified subsequent adjustment for marine control. For range observation R_{jm}, equation (4) is defined as:

$$B_{jm} = \frac{\partial F_{jm}}{\partial R_{jm}} = -1$$

$$A_{jm} = \frac{\partial F_{jm}}{\partial u_m^o, u_j^o} = \left[a_{jm} \quad -a_{jm} \right]$$

$$a_{jm} = \left[\frac{u_m^o - u_j^o}{R_{jm}}, \frac{v_m^o - v_j^o}{R_{jm}}, \frac{w_m^o - w_j^o}{R_{jm}} \right]^T$$

$$X_{jm} = \left[du_m \; dv_m \; dw_m \mid du_j \; dv_j \; dw_j \right]^T$$

$$W_{jm} = R_{jm} \text{ (computed)} - R_{jm} \text{ (observed)}.$$

The value R_{jm} is computed from the marine platform position and initial estimates of transponder positions to evaluate the misclosure vector W_{jm}. The design matrix B for all events becomes a negative unit matrix and the residual matrix V_{jm} then corresponds to the difference between the observed ranges R_{jm} and those observations corrected in the adjustment process.

3.2 Normal Equations

If P is the weight matrix for observed acoustical ranges, then the minimization function is given as:

$$\text{where} \quad = V^T P V + X^T P_X X - 2K^T(AX - V + W) \tag{5}$$

$$P_X = \begin{bmatrix} P_{x_j} & 0 \\ & \\ 0 & P_{x_m} \end{bmatrix} .$$

The weights P_X are determined from the uncertainties in the GPS navigation solutions and the apriori uncertainties for transponder positions. The introduction of these weights into the minimization problem represents a change to the geometric positioning theory presented in Mueller et al. (1973). After enforcing the minimization of equation (5) and eliminating the vector of Lagrange multipliers (K) and residual vector (V), the normal equations for platform and transponder positions can be written as:

$$\begin{bmatrix} N_{jj} & N_{jm} \\ & \\ N_{mj} & N_{mm} \end{bmatrix} \begin{bmatrix} X_j \\ \\ X_m \end{bmatrix} + \begin{bmatrix} U_j \\ \\ U_m \end{bmatrix} = 0 . \tag{6}$$

In this development, the marine platform positions X_j are the necessary link between the GPS constellation and the transponders. As these parameters are formally eliminated, the final form for the normal equations becomes:

$$NX_m + U = 0 \quad . \tag{7}$$

4. DATA SIMULATIONS

In the current analysis, a rectangular network of 25 transponder stations is visualized with a grid spacing of 3 minutes of arc. Simultaneous observations to a traversing marine platform were considered for two cases, where either five transponder stations participated in an event or where the number varied as a function of the maximum effective acoustical range. This scenario was extended to include three additional stations outside the basic network (Figure 3). These three stations were added to improve the geometry of the system and to eliminate the effect of critical configuration that networks of limited extent are subject. Transponders were located at an average depth of 2.5 kilometers with total variations in depth of 1 km.

In tne least squares adjustment, scale definition is provided implicitly by the observed ranges, while definitions for origin and orientation are required from external information. That information is in the form of constraint conditions imposed on the estimation problem. One choice for these external conditions is the "inner" constraints or free adjustment of Blaha (1971b), which produces a solution wherein the covariance matrix on adjusted parameters has minimum trace. Geometrically this implies that the first moments of all transponder station coordinates, as computed using initial coordinate values, will not change after the adjustment and that the sum of rotations of points around all three coordinate axes will be zero. An alternate condition is the imposition of weight constraints on marine platform positions consistent with the ten meter GPS navigation accuracy and/or on a selected subset of the transponder network initial coordinates. The effects of these conditions are discussed below.

An additional consideration is the design of the track patterns to be followed by the marine platform to assure adequate geometric strength for the recovery of the transponder positions. Track patterns are important for an adequate number of events involving individual transponders and to improve the geometric strength of the pyramid. In the analysis of this concept several track patterns were simulated, varying from an equally spaced pattern of parallel straight tracks to various subsets of the star and square pattern of Figure 4 which are reported herein. Although a systematic search for an optimal survey design was not accomplished, it was felt that the track geometries considered were sufficient to perform the intended task.

The observation frequency for double pyramid events was varied from 150 to 3400 meters of platform travel or separation between events. The majority of case studies were based on 300 meters travel per event. A substantial increase in the frequency of these events will not, in general, benefit the results since the platform-transponder geometry will change insignificantly between observations. Too low a rate will fail to produce a sufficient number of simultaneous events to tie the network together. Clearly a trade-off between geometric sampling and data reduction requirements should force a closer look at this point in future work. However, for the purposes of this paper, nominal rates of 150 to 300 meters travel per event provided satisfactory results.

5. ADJUSTMENT RESULTS

5.1 Inner Constraint Solution

A preliminary solution to the marine control problem was performed using inner constraints. In this case, the platform position solutions provided by GPS were adopted as initial coordinates during the time required to traverse track pattern A of Figure 4. Initial estimates for the coordinates of the transponder network were adopted based on assumed latitude and longitude solutions provided by GPS during the deployment of the transponders, with sea floor depth obtained by bathymetry. The apriori uncertainties for all initial platform and transponder positions did not enter into the least squares adjustment. Although the use of inner constraints did provide the minimum number of conditions necessary to obtain a solution, the solution was weak due to a lack of geometric strength. Transponder position recovery near the edge of the array was even weaker due to the edge effect. It was determined that an alternate approach for a satisfactory solution to the problem was required.

5.2 Establishment of Marine Control Using Weight Constraint Conditions.

Next, the simulation was repeated using the full twenty-eight station array. In this adjustment, weight constraints were enforced on marine platform positions consistent with a ten-meter standard deviation on each coordinate, the expected accuracy using high precision GPS navigation. Platform tracking pattern A was selected with an observation rate of 300 meters travel per event. Acoustical ranges were not included if the platform-transponder line of sound exceeded eight kilometers. A total of 610 simultaneous events, involving a minimum of five transponders per event, were measured. In addition to the platform position constraints, it was assumed that transponders 26, 27, and 28 were known to 300 meters in latitude and longitude and to 10 meters in depth. These weak constraints, however, imposed no major influence on the solution. The resulting positional uncertainties for the transponder network in the GPS Cartesian coordinate system are provided in Table 1. These results demonstrate that, interior to the network, positional accuracies approach the 30 to 50 centimeter level. As the boundary of the array is approached, uncertainties increase to 1 to 2 meters with less accuracy in some instances. This is to be expected since the number of simultaneous events involving edge transponders is less than for those more interior to the array in this case (edge effect). In addition, the geometry of the normal event along the rectangular path is limited in its contribution to the overall geometric strength provided to the solution. As will be seen below, the addition of tracks in patterns B and C strengthens the solution for edge transponders.

5.3 Mixed Constraints

A subsequent solution was performed in which the weight constraints of Section 5.2 were added to the inner constraint solution of Section 5.1. The full network of twenty-eight transponder positions was redetermined using tracking pattern A with an observation rate of 300 meters travel per event. Again, 610 simultaneous double pyramid events were processed. The results are given in Table 2. A comparison of this solution with the resulting position uncertainties from the previous case shows that the largest change to transponder positions occurs on the edge of the network. The improvement at some such locations is on the order of one meter or more. Improvement of a lesser degree is apparent in the interior of the network.

5.4 Variation in Platform Tracking Pattern

Although optimization of the tracking pattern was not thoroughly investigated, several patterns were examined in the simulations. For a sampling rate of 300 meters travel per event, three tracking patterns were examined (Figure 4). Solutions using mixed constraints were made where the number of simultaneous events from the three track patterns were 403, 535, and 583 respectively. Only the twenty-five transponders comprising the rectangular grid, numbers 1 through 25, were considered in this case. As additional rectangular survey lines were added to pattern A, the overall geometric strength of the transponder position determination was increased. The uncertainty of the exterior transponder locations demonstrated the greatest improvement, since observations from these locations underwent the strongest variation in geometry. The RMS uncertainty decreased from 2.69 to 1.17 meters as the rectangular tracks at 18 then 22 kilometers were added (Table 3). The interior stations showed mixed results as additional tracks were added.

However, the overall level of accuracy achieved in all cases for interior transponder positions was excellent, less than 70 centimeters. Thus, to fully exploit the double pyramid approach, it will be necessary to optimize the track geometry utilized in solving the marine control problem. This geometry will naturally depend on several factors such as water depth and transponder spacing.

6. Conclusion

This paper has provided a preliminary analysis of the utilization of GPS to establish ocean bottom control. The results indicate that a remote survey platform as a link between multiple GPS satellites and an acoustic deep ocean transponder network will allow the development of positional accuracies for the transponder array which approach one meter in the GPS coordinate frame. The key to this result is the adoption of platform position constraints consistent with high accuracy GPS navigational capabilities. In addition, the platform track geometry used to survey transponder locations will require optimization in order to exploit this approach to its fullest.

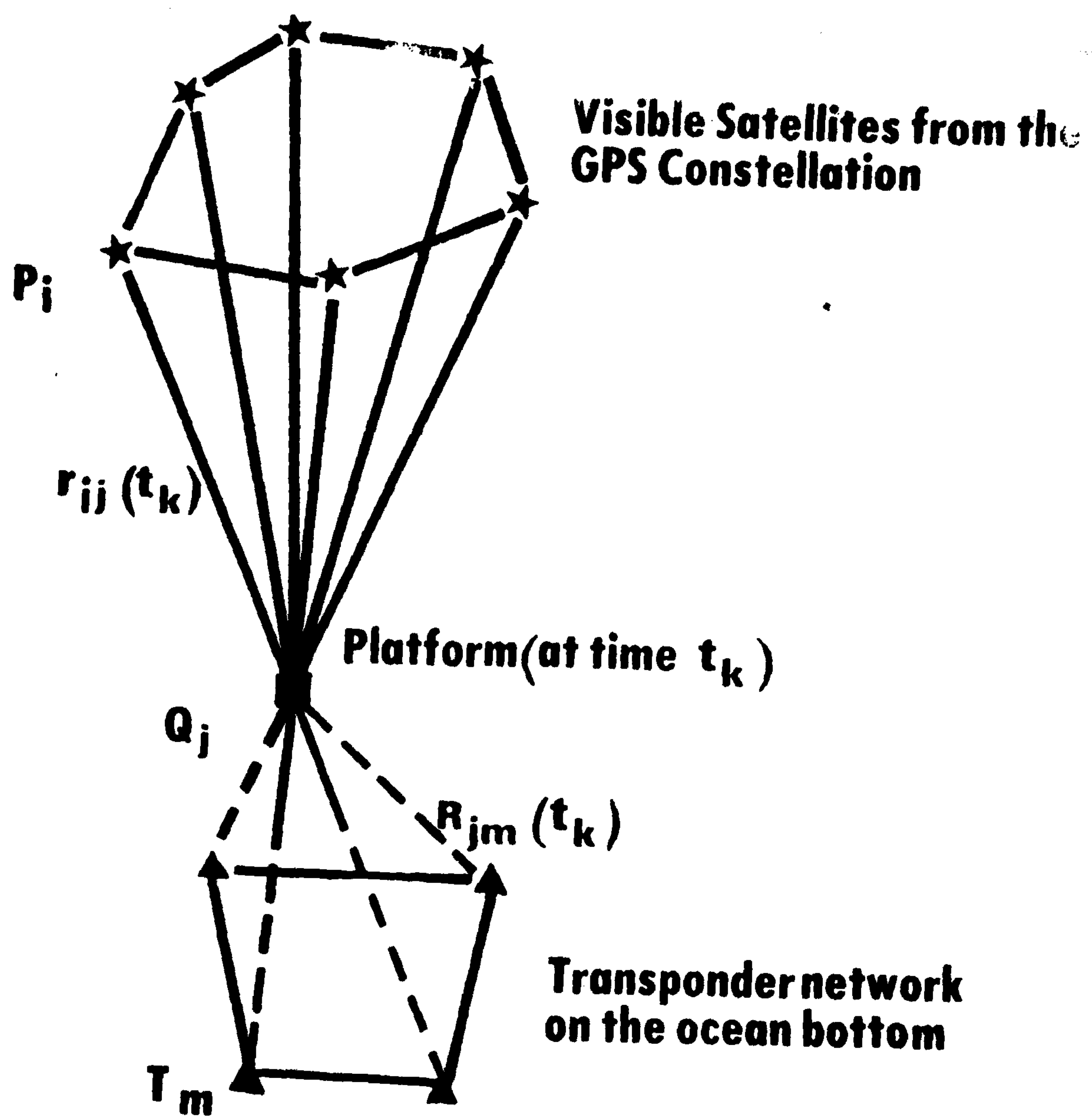


Figure 1: Double Pyramid Configuration for Observation of a Complete Event.

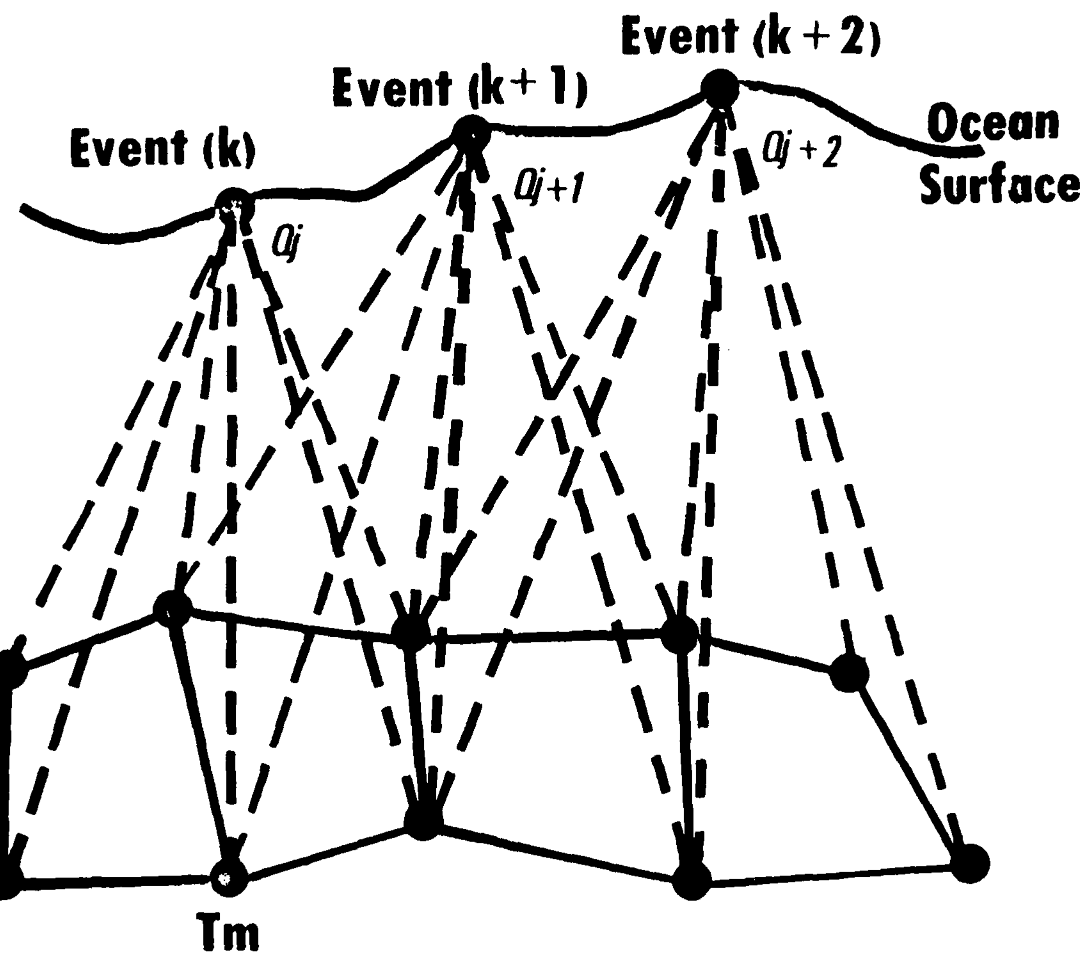


Figure 2: Normal Event Sequence with Observations to Multiple Transponders

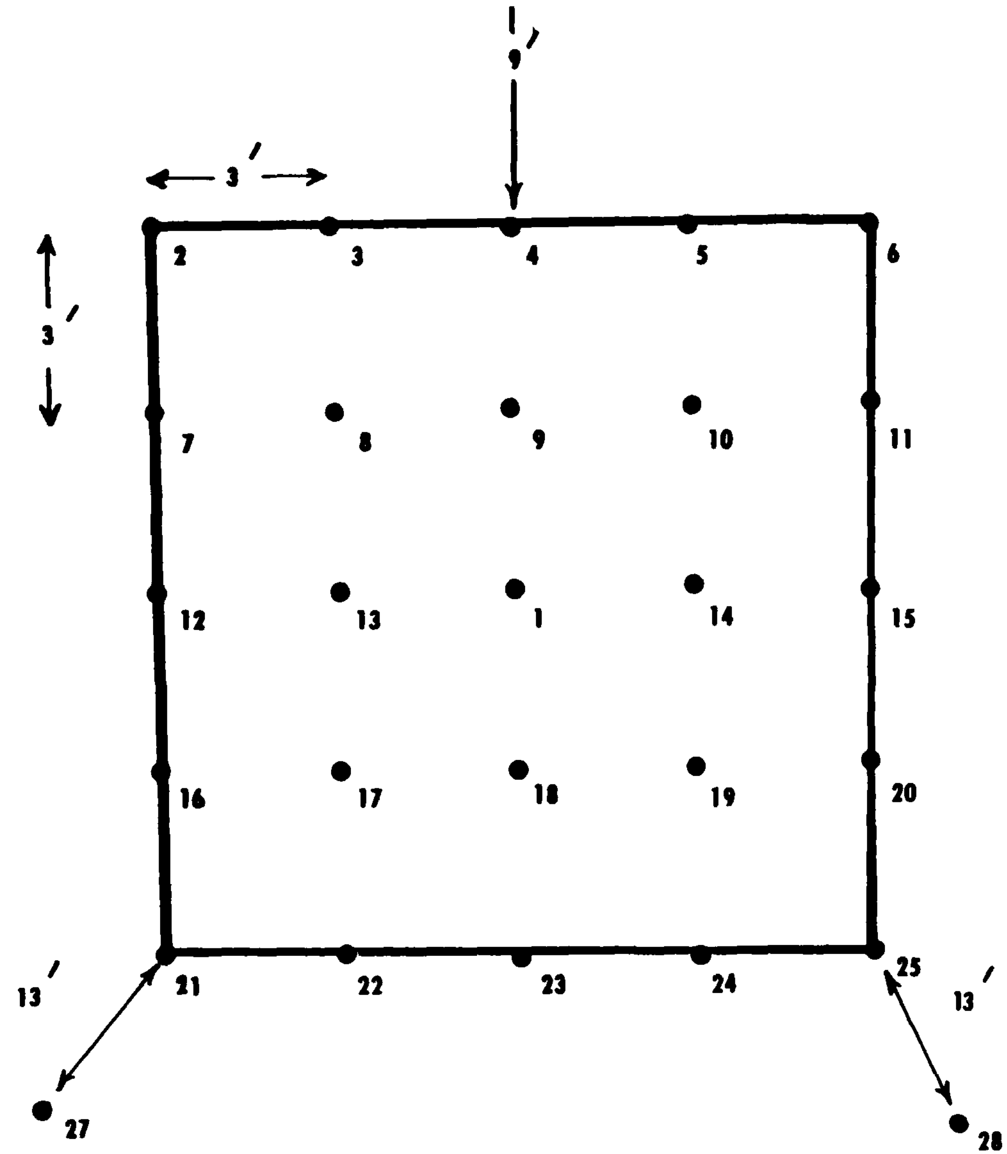
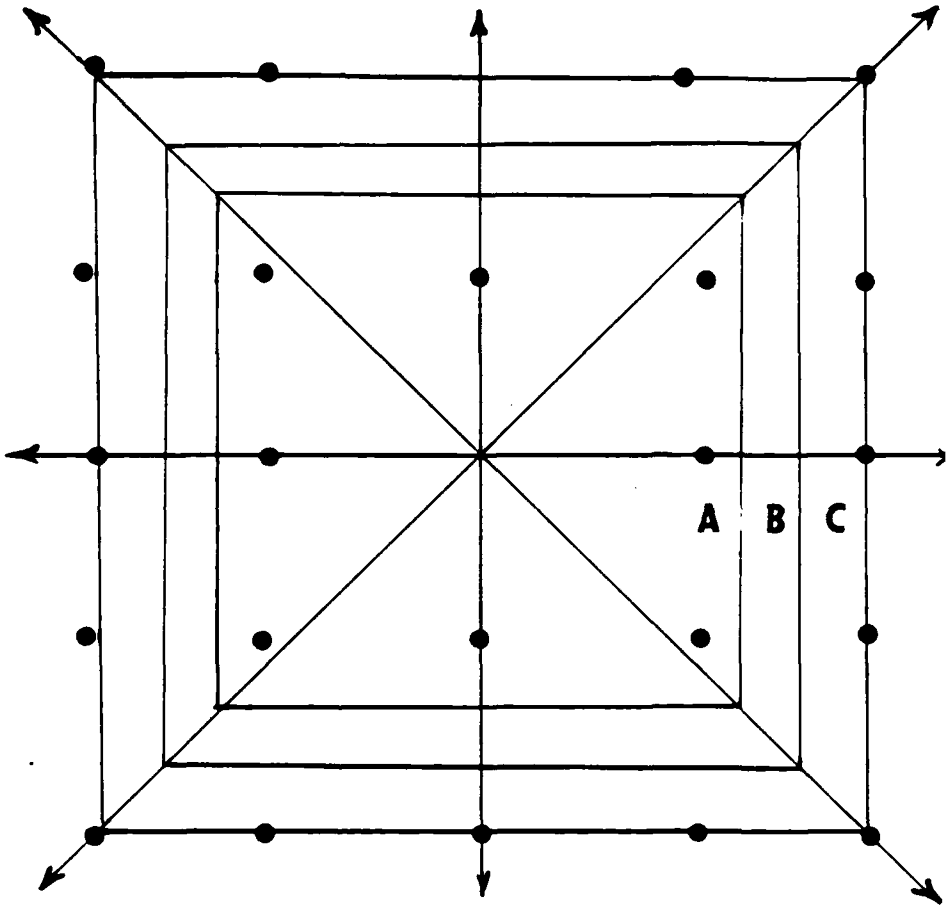


Figure 3: Acoustic Transponder Network

FIGURE 4. Composite of Platform Survey Patterns over the Transponder Network



Pattern	Description
A	Star + 15km square
B	Star + 15, 18km square
C	Star + 15, 18, 22km sq

Table 1: Uncertainty of Transponder Locations in GPS Cartesian Coordinate System using Weight Constraints from GPS Navigation Solutions

Transponder	X	Y	Z
1*	.48m	.49m	.44m
2	1.50	.89	2.34
3	.49	.48	.89
4	.74	.74	.70
5	3.22	3.41	5.12
6	.70	.96	1.67
7	.73	.54	.55
8*	.36	.31	.39
9*	.44	.44	.46
10*	.38	.42	.44
11	.38	.54	.43
12	.63	.46	.48
13*	.36	.31	.34
14*	.42	.47	.44
15	.51	.69	.51
16	.60	.49	.42
17*	.46	.46	.36
18*	.32	.32	.34
19*	.50	.51	.40
20	.56	.70	.44
21	.96	1.80	.51
22	.74	.59	.37
23	.69	.68	.39
24	.65	.90	.41
25	2.16	1.26	.61
26	.91	.93	1.66
27	1.88	1.70	2.13
28	1.56	1.82	1.91

*Interior Network Transponders

Table 2: Uncertainty of Transponder Locations in GPS Cartesian Coordinate System using Mixed Constraints

Transponder	X	Y	Z
1*	.46m	.46m	.42m
2	1.20	.81	2.04
3	.43	.45	.86
4	.70	.69	.65
5	1.84	1.91	2.98
6	.65	.82	1.51
7	.65	.52	.52
8*	.31	.29	.36
9*	.41	.41	.43
10*	.36	.38	.41
11	.37	.48	.41
12	.59	.43	.45
13*	.33	.29	.33
14*	.40	.44	.42
15	.48	.64	.48
16	.56	.45	.39
17*	.43	.43	.35
18*	.30	.30	.34
19*	.46	.47	.38
20	.52	.65	.40
21	.90	1.60	.45
22	.69	.53	.35
23	.64	.63	.38
24	.59	.83	.39
25	1.86	1.17	.53
26	.97	.91	1.79
27	.76	.79	.81
28	.87	.83	.78

*Interior Network Transponders

Table 3: Root Mean Square Coordinate Uncertainty as a Function of Survey Track Pattern

	Transponder Group	
Track Pattern	Interior	Exterior
A	.70m	2.69m
B	.58	2.38
C	.64	1.17

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